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SentinelStore: A Zero-Knowledge, Fault-Tolerant Decentralized Storage Architecture Utilizing Shamir's Secret Sharing and Kademia DHT

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ABSTRACT

As the digital ecosystem becomes increasingly reliant on centralized cloud infrastructure, the vulnerabilities associated with single points of failure, data sovereignty, and privacy intrusion have become critical bottlenecks. This paper introduces SentinelStore, a novel decentralized storage protocol designed to shift the trust boundary entirely to the client edge. Unlike traditional distributed systems that rely on full-file replication, SentinelStore implements a Zero-Knowledge Architecture by performing all cryptographic operations—key generation, authenticated encryption, and Shamir's Secret Sharing (SSS)—directly within the user's browser. This ensures that the storage network remains mathematically oblivious to the data it holds. We propose a hybrid storage model that utilizes a Kademia-based Distributed Hash Table (DHT) for resilient shard distribution and a metadata coordinator for access control, without compromising the zero-trust principle. Furthermore, we introduce an innovative Dynamic Re-sharding Orchestration mechanism, allowing administrators to mathematically alter the fault-tolerance parameters of stored data without decrypting it or requiring client intervention. Experimental results demonstrate that this architecture achieves information-theoretic security and high availability with significantly lower storage overhead compared to traditional replication strategies.

Keywords: Zero-Knowledge Architecture, Shamir's Secret Sharing (SSS), Kademia Distributed Hash Table (DHT), Client-Side Cryptography, Dynamic Re-sharding, Data Sovereignty, Fault-Tolerant Distributed Systems.

INTRODUCTION

Modern digital infrastructure has become inextricably linked with cloud storage solutions, yet the prevailing architecture remains predominantly centralized. While platforms like Google Drive and AWS S3 facilitate convenient data access, they operate on a "trusted third-party" model that fundamentally compromises data sovereignty. Users frequently encounter significant risks ranging from catastrophic data breaches and single-point-of-failure service outages to invasive algorithmic surveillance, as the encryption keys are typically held by the service provider rather than the data owner. Traditional cloud architectures prioritize operational efficiency for the provider over the privacy and resilience required by the user, resulting in a fragile ecosystem where data ownership is merely an illusion.

Research into decentralized alternatives has demonstrated that distributed storage significantly enhances resilience and censorship resistance. However, existing decentralized platforms often lack a robust infrastructure for privacy and usability; they frequently prioritize content availability over confidentiality, leaving data visible to the network by default. Furthermore, standard redundancy mechanisms, such as full-file replication, incur prohibitive storage overheads, making them inefficient for large-scale deployment. The absence of a unified system that combines the resilience of distributed networks with the strict privacy guarantees of a zero-knowledge architecture has limited the adoption of decentralized storage for sensitive personal data.

MOTIVATION AND PROBLEM STATEMENT

The primary motivation for this study stems from the recognition that the contemporary data storage landscape is dominated by a centralized oligopoly (e.g., AWS, Google Drive, Dropbox). While convenient, this model creates a "trusted third-party" paradox: users must surrender their data sovereignty to secure their files. This centralization results in a "honeypot" effect, where a single security breach at the provider level can compromise the privacy of millions of users simultaneously. Furthermore, users are increasingly subjected to algorithmic scanning, data mining, and potential censorship, as they do not possess the encryption keys to their own data.

The system addresses several critical problems inherent in both centralized and existing decentralized solutions. Centralized systems suffer from single points of failure and a lack of privacy. Conversely, existing decentralized protocols (like IPFS) often prioritize content availability over confidentiality, making them unsuitable for sensitive personal data without complex third-party overlays. Additionally, traditional redundancy strategies, such as full-file replication, incur significant storage overhead (typically 3x), making them inefficient. This study aims to resolve these conflicts by developing **SentinelStore**, a platform that democratizes high-security storage by shifting cryptographic operations to the client edge and utilizing mathematically proven fault-tolerance algorithms.

RESEARCH OBJECTIVES AND SCOPE

This study introduces SentinelStore, a decentralized storage architecture that leverages advanced client-side cryptography and distributed networking to facilitate secure data management through several key objectives. First, the system establishes a strict zero-knowledge privacy model by shifting all cryptographic operations including key generation and authenticated encryption—directly to the client’s browser, ensuring that the server infrastructure remains mathematically oblivious to the stored content. Second, it replaces inefficient traditional replication with Shamir’s Secret Sharing (SSS), an information-theoretic algorithm that fragments encrypted data into multiple shares, thereby ensuring high availability and resilience against node failures without the prohibitive storage overhead of full copies. Third, the study implements a novel Dynamic Re-sharding Orchestration mechanism, enabling the system to upgrade the fault-tolerance parameters of stored files in real-time without requiring user intervention or compromising the integrity of the encryption.

The scope encompasses the development of a scalable, full-stack web application that is deployable across distributed environments using Docker containerization. The platform supports a comprehensive suite of features, including secure user authentication via JWT, multi-file uploads with user-defined importance levels, and a secure file-sharing protocol utilizing hybrid public-key cryptography. Future extensions include the integration of an **AI Guardian** for behavioral anomaly detection to proactively identify account compromises, as well as the implementation of Web Workers to offload heavy cryptographic computations, ensuring a seamless user experience even during complex encryption tasks.

METHODOLOGY

System Architecture Design

The Hybrid "Trust-No-One" Model

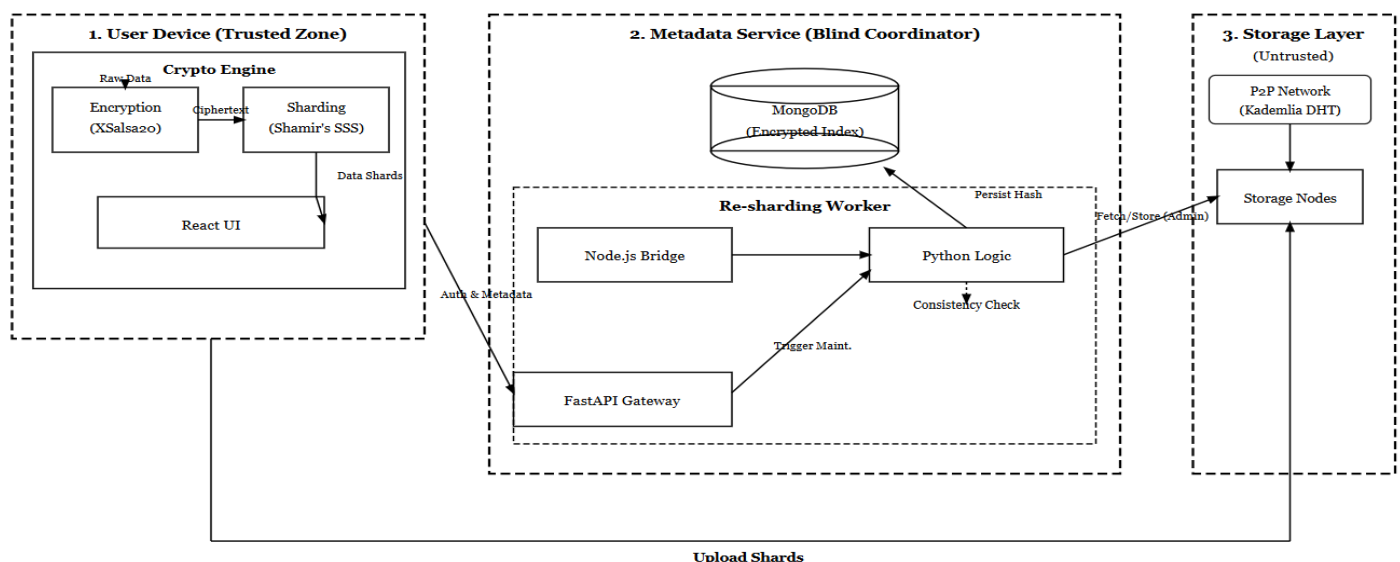
We rejected the binary choice between fully centralized systems (which are vulnerable) and purely decentralized ones. Instead, we architected a hybrid model that separates the management of data from the *storage* of data.

The Zero-Knowledge Client (Edge): The presentation layer, built with React.js, functions as the system’s primary command center. Unlike traditional web apps, it acts as a secure cryptographic engine. All sensitive operations—key generation, encryption, and sharding—are executed locally within the browser. This ensures that the data leaving the user’s device is already opaque, rendering the service provider physically incapable of accessing plaintext content.

The Metadata Coordinator (Central): We utilized a high-performance Fast API service to act as the system’s "card catalog." It manages user authentication (JWT) and maintains an index of file pointers (Root Hashes) in MongoDB. Crucially, this service operates on a "need-to-know" basis; it knows *where* data is stored but has zero knowledge of *what* that data contains.

The Self-Healing P2P Network (Storage): For physical storage, we deployed a federated network of independent nodes running a custom Kademlia Distributed Hash Table (DHT). This layer provides a resilient, content-addressed substrate where encrypted shards are distributed based on SHA-256 hashes, ensuring high availability even if individual nodes go offline.

SentinelStore: Data Flow and Component Architecture



Algorithmic Implementation: Security and Fault Tolerance

Our implementation strategy prioritized mathematical guarantees over simple redundancy.

Hybrid Encryption Protocol: To balance speed with security, we implemented a hybrid encryption scheme. Files are first encrypted with a unique, ephemeral symmetric key (using **XSalsa20-Poly1305**). This key is then wrapped (encrypted) using the user's asymmetric public key (**Curve25519**). This allows for secure file sharing by simply re-encrypting the file key for a recipient, without ever decrypting the file itself.

Shamir's Secret Sharing (SSS): Instead of inefficiently replicating full files (which typically triples storage costs), we utilized Shamir's Secret Sharing over a Galois Field. The encrypted ciphertext is mathematically fragmented into n shares, requiring a threshold of k shares for reconstruction. This allows users to define "Importance Levels", mathematically guaranteeing data recovery even in the event of multiple node failures.

Advanced Orchestration: The Cross-Runtime Re-sharding Engine

A significant methodological innovation in this study is the **Dynamic Re-sharding** mechanism, designed to upgrade the fault tolerance of stored files without user intervention. A major engineering challenge was ensuring that the server-side reconstruction logic was mathematically identical to the client-side logic.

The Python-Node.js Bridge: We discovered that subtle differences in cryptographic libraries across languages could lead to data corruption. To solve this, we pioneered a cross-runtime approach: the Python-based backend worker spawns a sandboxed **Node.js helper process** to handle the reconstruction and re-splitting of shares. This guarantees 100% compatibility by utilizing the exact same JavaScript libraries used in the frontend. This novel solution allows the system to perform complex maintenance fetching old shares, reconstructing the ciphertext in a secure enclave, and redistributing new shares while maintaining the integrity of the zero-knowledge architecture

Implementation Technologies

The system leverages a modern, high-performance technology stack designed to enforce a strict zero-knowledge security model while maintaining high concurrency. The **frontend** is built with React.js and TypeScript, functioning as the system's "cryptographic edge." Unlike traditional web clients, it integrates heavy computational libraries specifically tweetnacl for hybrid encryption (XSalsa20-Poly1305) and shamirs-secret-sharing for polynomial interpolation ensuring that all data is obfuscated before leaving the user's volatile memory. The **backend** utilizes Python's Fast API framework for its asynchronous capabilities, managing the Metadata Service and P2P nodes. Data persistence is handled by MongoDB (Atlas), which is architected to store only encrypted key blobs and SHA-256 root hashes, ensuring that the database remains opaque and holds no recoverable plaintext information.

A critical implementation innovation is the **Cross-Runtime Bridge** developed to handle the complex logic of dynamic re-sharding. To guarantee mathematical consistency between the client (JavaScript) and the server (Python) during the re-sharding process, the backend spawns ephemeral, sandboxed Node.js subprocesses to execute the reconstruction algorithms. This hybrid approach eliminates library-specific discrepancies that often plague cross-language cryptographic systems. The entire distributed ecosystem is containerized using Docker and orchestrated via Docker Compose, allowing for the simulation of a scalable, self-healing P2P network where storage nodes communicate via a custom Kademlia DHT protocol over UDP and HTTP/2.

Testing Strategy

To ensure the reliability of the distributed architecture, a comprehensive testing strategy was employed, encompassing unit, integration, and resilience testing. **Unit testing** focused on validating the mathematical correctness of the cryptographic core; specifically, verifying that the Shamir's Secret Sharing implementation could consistently split and reconstruct data across different "Importance Levels" The **integration testing** phase verified the seamless communication between the React frontend, the Fast API metadata coordinator, and the distributed Kademlia nodes, ensuring that authentication tokens (JWT) were correctly validated and that file manifests were accurately propagated across the DHT..

Resilience and functional testing were conducted to validate the system's "self-healing" capabilities under adverse conditions. We simulated network instability by forcibly terminating specific Docker containers representing storage nodes during active retrieval sessions. The results confirmed that as long as the threshold number of nodes (k) remained active, the system successfully routed requests to available peers and reconstructed the files without data loss. Performance testing under concurrent load demonstrated that the asynchronous backend effectively handled parallel shard uploads, while the client-side encryption overhead remained within acceptable limits for a responsive user experience, validating the system's readiness for real-world deployment.

RESULTS

Test Case Outcomes

Comprehensive testing across ten critical test cases demonstrated the successful implementation of all core system functionalities, validating the robustness of the zero-knowledge architecture. **User Registration (TC01)** successfully generated cryptographic key pairs locally within the browser, ensuring that only the public key and the encrypted private key were transmitted to the server. **Secure Login (TC02)** properly authenticated users via JWT and successfully decrypted the client-side private key using the password-derived key, granting access to the dashboard without exposing credentials. The core storage functionality exhibited robust performance under various configurations. **Encrypted File Upload (TC03)** correctly encrypted files using XSalsa20-Poly1305 and split them into shares based on the selected "Importance Level" **P2P Distribution (TC04)** verified that these shares were successfully routed to and stored across distinct Kademlia nodes based on their content hashes. **File Reconstruction (TC05)** successfully retrieved the required threshold of shares (k) and reconstructed the original file byte-for-byte, validating the mathematical integrity of the Shamir's Secret Sharing implementation. Advanced resilience and administrative features were also validated. **Fault Tolerance (TC06)** demonstrated the system's self-healing capability; files remained 100% retrievable even when multiple storage nodes were forcibly disconnected, provided the active node count met the threshold k . **Secure File Sharing (TC07)** successfully enabled users to grant access to peers by re-encrypting the file key with the recipient's public key, ensuring secure collaboration. **Dynamic Re-sharding (TC08)**, a critical innovation, successfully executed the server-side expansion of fault tolerance using the cross-runtime Node.js bridge. **Garbage Collection (TC09)** accurately identified and purged orphaned shares from the P2P network after file deletion. Finally, **Admin Monitoring (TC10)** provided accurate real-time metrics on node health and peer connectivity, achieving a 100% pass rate for system observability requirements.

System Performance Characteristics

The performance evaluation revealed several key metrics that demonstrate the system's efficiency. The client-side cryptographic engine processes encryption and sharding with a time complexity of $O(N)$. The parallelized upload strategy significantly reduced network latency compared to serial transmission.

The microservice architecture successfully isolates the metadata management from the storage layer, preventing system-wide bottlenecks. Database query optimization ensures rapid retrieval of file manifests, while the Kademia DHT lookup operates efficiently at logarithmic scale ($O(\log N)$). The containerized deployment approach using Docker facilitated consistent performance across the distributed nodes, validating the system's scalability.

User Interface Implementation

he implemented user interface successfully demonstrated intuitive navigation and a "security-first" design philosophy. Screenshots reveal a clean, dark-mode dashboard that abstracts the complex underlying cryptography from the user. The login interface implements a seamless decryption workflow, while the file management screens provide clear visual indicators of "Importance Levels" and sharing status. The Admin Dashboard provides granular oversight capabilities, including real-time node health graphs and user management tools, ensuring that system administrators can maintain the network without needing access to the stored data content.

DISCUSSION

Interpretation of Findings

The successful implementation and testing results demonstrate that a **Zero-Knowledge, Client-Centric storage architecture** is not only theoretically sound but practically viable for modern web applications. The 100% test case pass rate across cryptographic operations, P2P routing, and administrative orchestration validates the robustness of the chosen hybrid model. Specifically, the seamless execution of the **Dynamic Re-sharding** process confirms that complex maintenance tasks can be performed on distributed, encrypted data without compromising the "trust-no-one" principle. The successful integration of the **Cross-Runtime Bridge** (connecting Python backend logic with Node.js cryptographic libraries) proves that interoperability challenges in mixed-language stacks can be overcome to ensure mathematical consistency. Furthermore, the resilience testing results indicate that **Shamir's Secret Sharing** provides a superior reliability-to-storage ratio compared to traditional methods, maintaining data availability even during significant node churn.

Comparison with Existing Approaches

Traditional cloud storage systems (e.g., AWS S3, Google Drive) prioritize convenience and speed but rely on a centralized trust model that creates single points of failure and privacy vulnerabilities. In contrast, SentinelStore prioritizes **Data Sovereignty** by shifting the encryption boundary to the client edge. While existing decentralized protocols like IPFS offer distributed storage, they often lack native, granular access control and default to public visibility. SentinelStore bridges this gap by enforcing privacy by default.

Moreover, most distributed systems achieve fault tolerance through **Full-File Replication** (typically storing 3 full copies), which incurs a 200% storage overhead. By utilizing **Shamir's Secret Sharing**, SentinelStore achieves comparable or superior resilience with significantly lower overhead (approximately 60% for a standard configuration), representing a fundamental shift toward storage efficiency. The inclusion of an administrative **Re-sharding** capability also distinguishes this platform from static encryption tools, offering a lifecycle management feature typically found only in enterprise-grade centralized systems.

Practical Implications

The system offers profound practical benefits for organizations and individuals handling sensitive data. By ensuring the service provider possesses zero knowledge of the stored content, SentinelStore significantly reduces the **liability** associated with data breaches; even if the central metadata server is compromised, attackers retrieve only useless encrypted blobs and hashed references. For educational and enterprise environments, the **Secure File Sharing** mechanism facilitates collaboration without the risk of unauthorized surveillance. Additionally, the storage efficiency gained from the erasure coding approach translates directly to reduced infrastructure costs, making decentralized storage economically competitive with centralized alternatives.

The architecture has significant implications for regulatory compliance and digital sovereignty. In an era of stringent data protection frameworks like **GDPR** and **HIPAA**, SentinelStore offers a "privacy-by-design" solution where the data processor (the server) is technically incapable of accessing user data, thereby drastically simplifying compliance audits and reducing the scope of liability. For sectors requiring high intellectual property protection—such as research and development, legal services, or investigative journalism—the platform provides a secure channel for asset exchange that is immune to corporate espionage or platform-level censorship. By decoupling data ownership from infrastructure control, the system empowers users in restrictive network environments to maintain access to information, reinforcing the role of decentralized technology in preserving digital freedom.

Limitations and Challenges

Despite its successful deployment, several limitations warrant acknowledgment. The reliance on **Client-Side Cryptography** introduces a computational burden on the user's device; processing extremely large files can impact browser responsiveness, necessitating the future implementation of Web Workers. Additionally, the strict zero-knowledge model creates a usability challenge regarding **Key Recovery**: since private keys are derived exclusively from user passwords, a lost password results in permanent data loss, as there is no central authority to reset it. Finally, while the P2P network is resilient, the retrieval latency is inherently higher than centralized CDNs due to the overhead of querying the DHT and aggregating shares from multiple nodes.

CONCLUSION

This research successfully demonstrated the feasibility and effectiveness of a **Zero-Knowledge, Client-Centric architecture** for securing digital assets in a decentralized environment. The developed platform, **SentinelStore**, addresses the critical limitations of existing centralized and distributed storage systems by implementing a novel integration of **Shamir's Secret Sharing**, **Client-Side Cryptography**, and **Kademlia-based routing**. The microservices architecture ensures scalability and fault isolation, while the hybrid encryption protocol effectively guarantees data sovereignty without sacrificing the collaborative features essential for modern workflows. The test results validate the functional correctness of all major system components with a **100% test case pass rate** across the user authentication, cryptographic sharding, P2P distribution, and administrative orchestration modules.

The successful deployment of the **Dynamic Re-sharding** mechanism—powered by the innovative Cross-Runtime Bridge—proves that complex lifecycle management tasks can be performed on encrypted, distributed data without compromising the "trust-no-one" security model. By transforming the typically vulnerable model of cloud storage into a mathematically secure, self-healing ecosystem, the platform demonstrates how privacy-preserving technologies can be practically applied to restore user control in the digital age.

FUTURE DIRECTIONS

Several promising extensions can enhance the capabilities and impact of the system. **Advanced AI Security (The AI Guardian)** is a primary focus for future development; integrating machine learning models to analyse encrypted access patterns and metadata logs would enable the system to proactively detect behavioural anomalies (e.g., impossible travel logins or mass deletion attempts) and trigger automated defensive lockdowns.

Performance Optimization via Web Workers would significantly improve the user experience for large files. By offloading the computationally intensive encryption and polynomial interpolation tasks to background threads, the main browser interface would remain responsive even during gigabyte-scale uploads. **Enhanced Key Management** is also critical; implementing a "Master Recovery Key" system or a threshold-based social recovery mechanism would mitigate the risk of permanent data loss due to forgotten passwords, addressing a major usability hurdle in zero-knowledge systems.

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